

# **Doppler Global Velocimeter Measurements of the Vortical Flow Above A Thin Delta Wing**

by

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## **Abstract**

A new measurement technique is being developed by NASA to measure off-surface flow fields. This method, Doppler global velocimetry, will allow quantification of complex three-dimensional flow fields at video camera rates. The entire flow field structure within a selected plane is measured simultaneously rather than by scanned, point-by-point measurements using conventional laser velocimetry. Data obtained using this technique will be used to correlate with other data sets for verification, and following verification, provide a quantified, highly detailed definition of the flow field. This will help to improve the understanding of fluid physics, supplement and broaden the database required to validate and refine computational fluid dynamics (CFD) models, and improve aircraft design methodology. To assess the capability of the technique, velocity measurements of the vortical flow field above a thin 75-degree delta wing were made in the NASA - Langley Basic Aerodynamics Research Tunnel. Preliminary comparisons of the results were made with similar measurements obtained using a three component laser velocimeter indicate that this technique is capable of describing the entire three-component velocity flow field simultaneously within a measurement plane in real time.

## **Nomenclature**

ALF	Absorption line filter, Iodine vapor
$c$	Speed of light, m/sec
$\hat{i}$	Laser beam propagation direction
$\hat{o}$	Collected scattered light direction
$V$	Velocity of a particle passing through the laser beam, m/sec
$X$	Cross tunnel coordinate, m
$Y$	Vertical coordinate, m
$Z$	Streamwise coordinate, m
$\Delta\nu$	Doppler shift frequency, Hz
$\nu$	Laser output frequency, Hz
$\theta$	Angle between the laser propagation direction and the collected scattered light, deg

## **Introduction**

Designers of modern aircraft need improved design methods which exploit complex three-dimensional flow fields to enhance maneuverability and increase lift at certain critical stages in the flight regime. Fighter aircraft, for example, operating at high angles of attack generate vortices to aid in increasing performance. However, these vortices may also interact with the airframe or other external systems resulting in buffeting and the potential for fatigue-related structural problems. With increased knowledge of the flow field, designers will be able to exploit the increase in performance resulting from vortical flow while avoiding the problems. Similarly, high speed civil transports flying at low speed may require higher lift than available from classic wing designs. Designers have solved this problem by using leading-edge vortex flow control devices to obtain high lift and low drag on slender, highly swept wings. The development of design methods which take advantage of these complex flow fields has been hampered in the past because of the lack of quantitative nonintrusive flow field measurements.

In an effort to expand and improve these measurements, NASA has initiated the development of a flight research instrument system to provide off-body velocity measurements to validate and supplement wind tunnel and CFD data. Flight test experiments are needed because wind-tunnel results may be affected by facility uniqueness and experimental techniques. Also, wind-tunnel results on scaled models may differ from those on full-scale flight vehicles because of Reynolds number effects.

The flight instrument system is based on a new nonintrusive measurement technique, Doppler global velocimetry, developed and patented by the Northrop Corporation, reference 1. The technique yields global, simultaneous, three-dimensional velocity measurements of the flow field within a selected measurement plane. These global velocity maps can be obtained at video camera rates from which mean velocity components and velocity time histories can be extracted.

In this paper, a prototype Doppler global velocimeter instrument system is described. In addition, results of a flow field investigation conducted in the Basic Aerodynamics Research Tunnel are assessed to determine the potential of the technique. The vortical flow field above a 75-degree delta wing was chosen since it represents a class of flow with increased application on high performance aircraft, and the results could be compared with earlier laser velocimeter measurements made under the same conditions. These tests are part of an ongoing research and development program to develop and refine the Doppler global velocimeter for flight applications. The program will culminate with a demonstration flight of an operational instrument system on a high performance aircraft.

## **Doppler Global Velocimetry**

The principle of operation of the Doppler global velocimeter, DGV, is based on the shift in optical frequency of scattered light from objects passing through a laser beam. This principle was first exploited by Yeh and Cummins in 1964, reference 2, to develop the reference beam, laser Doppler velocimeter (LDV). As depicted in figure 1, scattered light collected by a detector located along the direction  $\hat{o}$ , from particles passing through a laser beam propagating in direction  $\hat{i}$ , is Doppler shifted based on a velocity in the direction  $(\hat{o} - \hat{i})$ . This relationship is expressed by:

$$\Delta v = \frac{v_o (\hat{o} - \hat{i}) \bullet V}{c} \quad (1)$$

where  $\Delta v$  is the Doppler shifted frequency,  $v$  is the laser frequency,  $V$  is the particle velocity, and  $c$  is the speed of light.

Whereas the LDV used heterodyning techniques to obtain the Doppler frequency, the DGV measures the optical frequency directly using an absorption line filter, (Iodine vapor cell), as a frequency discriminator. Since the absorption line filter (ALF) measures light frequency directly, it is not restricted to scattered light from a single particle collected by a single detector as in the LDV. Thus if the laser beam is expanded into a light sheet and the detector replaced by a CCD camera, global velocity measurements can be obtained. A pictorial view of this method is shown in figure 2. The function of the reference camera shown in figure 2 is to obtain an intensity map from the illuminated particle field without the influence of the Doppler effect. This map is used to normalize the signal camera output and thus remove intensity variations caused by effects other than velocity, e.g., variations in particle number density, particle size, and laser power density. Further details on the operation of the DGV are given in references 1, 3, and 4.

As stated above and depicted in figure 1, the configuration measures the velocity component in the direction  $(\hat{o} - \hat{i})$ . Moving the detector, thus changing the direction of  $(\hat{o} - \hat{i})$ , allows another velocity component to be measured. Likewise, changing the laser beam propagation direction,  $\hat{i}$ , will also change the direction of the measured velocity component. Therefore, a three-component DGV can be constructed by using multiple detectors and/or multiple laser beam propagation directions.

### **Flow Field Investigation Above a 75-degree Delta Wing**

The potential of the Doppler global velocimeter was investigated by measuring the vortical flow field above a 75-degree delta wing in the Basic Aerodynamics Research Tunnel, BART. The facility, reference 5, was an open return tunnel with a test section 0.71 m high, 1.02 m wide and 3.07 m long. A maximum velocity of 67 m/sec could be obtained in the test section with a test Reynolds number per meter of 0.43 million. The airflow entering the test section was conditioned by a honeycomb structure, four antiturbulence screens, and an 11:1 contraction ratio. The freestream turbulence intensity was less than 0.08 percent for all flow conditions. The propylene glycol vaporization/condensation generator developed for vapor screen flow visualization was used as the source of particles for the experiment. The particles were injected upstream of the honeycomb structure and have a size distribution which peaks at 0.7  $\mu\text{m}$  with a skewed distribution to a maximum of 10  $\mu\text{m}$ , reference 6.

An Argon ion laser operating in TEM<sub>00</sub> mode with an etalon to maintain single longitudinal mode at 514.5 nm was used as the light source. The output beam was directed to one of three cylindrical lenses to form a light sheet with the desired propagation direction to facilitate the measurement of three velocity component directions:  $\hat{i}_1$ ,  $\hat{i}_2$ , and  $\hat{i}_3$ . The receiver optical system consisting of the collecting lens, beam splitter, ALF, and CCD cameras was located 53 degrees from the streamwise (tunnel centerline) direction in the horizontal plane, figure 2. A photograph of the receiver optical system viewing particles in the vortical flow passing through the light sheet above the delta wing is shown in figure 3.

The outputs from the reference and signal cameras were processed by both an analog normalization circuit and a digital dual frame grabber, reference 4. The analog processor consists of an analog divider circuit that normalizes the signal camera output by the reference camera signal in real time. The resulting signal is converted to a standard RS-170 video signal that was stored, along with the two camera signals, on a 450-line video disk recorder. The digital dual frame grabber simultaneously acquires a video frame from both cameras. The amplitudes of the measured light intensities for a given pixel in each frame are used to address a lookup table cell containing the precomputed normalization value for those amplitudes. The resulting normalized image is passed, along with the original frames, to a microcomputer for further processing and storage.

A stainless steel 75-degree delta wing, 0.57 m in length, with sharp leading edges was placed in the tunnel at an angle of attack of 20.5 degrees. The tunnel dynamic pressure was set to 402 N/m<sup>2</sup> which yields a freestream velocity of 40 m/sec. The laser light sheet was placed perpendicular to the tunnel centerline at the 70-percent chord location on the model. These conditions match the model and tunnel settings used to acquire three component fringe type, laser velocimeter measurements in the investigation presented in references 5 and 7. The results of the previous study will be used as the standard for comparison with the present DGV measurements.

The laser velocimeter, LV, measurements obtained at the 70-percent chord location are shown in figure 4. The gray scale represents contours of streamwise velocity and the arrows represent the velocity vector of the circular flow within the plane perpendicular to the streamwise direction. Note that the streamwise velocity is accelerated to twice the free stream value at the vortex core. The circular flow is compressed by the wing and accelerated to 1.5 times the free stream value as the flow expands outward below the core. These measurements will be resolved in the component directions established by the DGV geometry to

minimize errors induced by coordinate transformation. That is, with the laser propagation direction shown in figure 2, (forward scatter), the DGV measurement direction is 18.5 degrees from streamwise in the horizontal plane, figure 5. The resolved LV measurement velocities are shown in figure 6. With the laser propagating in the opposite direction from figure 2, (backscatter), the measurement direction will be 71.5 degrees from streamwise in the horizontal plane, figures 7 and 8. The third component is obtained by propagating the laser from the top of the tunnel (side scatter) which yields the measurement directed 53 degrees from streamwise elevated 45 degrees above the horizontal plane, figures 9 and 10.

Example DGV data obtained with the digital dual frame grabber will be used to compare with the LV data. A single frame of flow field data representing each measurement component was selected. Each pixel within the normalized image was gray-scale coded based on its collected scattered light intensity. Frames representing the three measurement components are shown in figures 11 - 13. An assessment of these figures must include the influence of viewing perspective, misalignment within the DGV optical system, and effects of variations in the particle number density. Viewing perspective results in keystoned images with foreshortening in the horizontal direction for the optical arrangement used, figures 2 and 3. The keystone effect is illustrated by obtaining an image of a card with a square grid placed in the light sheet position, figure 14. Other distortions of the image caused by imperfections in the optical system will also result in spatial uncertainties. Further, optical distortions following the beamsplitter cause corresponding pixels in the two cameras to view different portions of the laser light sheet and thus be unrelated. This problem is accentuated in regions of large particle number density gradients such as in the vortex core and at the edges of the vortex flow, e.g., the thin gray scale rings at the edges of the images in figures 11 - 13.

While these errors are present in the DGV data, their removal is straight forward using standard image processing techniques. If the transfer function for the optical path for each camera is determined, images viewed by that camera can be corrected for perspective effects and optical distortions. For example, the image of the grid in figure 14 would be warped using image processing techniques until it matches the actual grid. This warping algorithm would then be used to apply the same modification to each image of the flow field. Once the images from each camera are corrected, they should overlay, pixel-by-pixel, with sufficient precision to obtain a normalized image dependent only on the intensity variations induced by the ALF. These algorithms are presently being developed and will be applied to the original reference

camera and signal camera images with normalization applied by computer.

Even without these corrections, it is still possible to compare the DGV data with the resolved LV data to look for similar trends in the measurements. For comparative purposes, the visual effects of the perspective distortion can be reduced by considering only the left vortex as outlined in figures 6, 8, and 10. Overlaying contours of velocity from the resolved LV data onto the DGV data images yields the comparative figures 15 - 17. Figure 15 shows circular contours from the LV data overlaying the circular gray bands in the DGV image. Figure 16 shows an opposing diagonal peak and valley in the LV data overlaying a similar structure in the DGV image. Finally, in figure 17, a similar pattern is found except the peak and valley are aligned vertically. Therefore, even with optical distortion, perspective differences, pixel misalignment, and uncertainties due to comparisons of an instantaneous data set with averaged LV results, the DGV data still compares favorably with the LV data indicating the potential capabilities of this technique.

## Summary

A new measurement technique, Doppler global velocimetry, has been described along with results from an experimental investigation to assess the potential of this technique for flow field diagnostics. The results of these tests, when compared to conventional laser velocimeter measurements, indicate that this robust technique is capable of describing the entire three component velocity flow field simultaneously within a measurement plane in real time. Further investigations are being conducted to correct the deficiencies described and to refine the measurement technique for flight applications.

## References

1. Komine, H.; Brosnan, S. J.; Litton, A. B.; and Stappaerts, E. A.: *Real Time, Doppler Global Velocimetry*, AIAA 29th Aerospace Sciences Meeting, Reno, NV, paper no. AIAA-91-0337, January 7-10, 1991.
2. Yeh, Y.; and Cummins, H. Z.: *Localized Fluid Flow Measurements with a He-Ne Laser Spectrometer*, Applied Physics Letters, vol. 4, no. 10, pp. 176-178, May 1964.
3. Meyers, J. F.; and Komine, H.: *Doppler Global Velocimetry - A New Way to Look at Velocity*, ASME 4th International Conference on

Laser Anemometry, Advances and Applications, Cleveland, OH, August 5-9, 1991.

4. Meyers, J. F.; Lee, J. W.; and Cavone, A. A.: *Signal Processing Schemes for Doppler Global Velocimetry*, IEEE - 14th International Congress on Instrumentation in Aerospace Simulation Facilities, Rockville, MD, October 27-31, 1991.
5. Sellers, W. L., III; and Kjelgaard, S. O.: *The Basic Aerodynamics Research Tunnel - A Facility Dedicated to Code Validation*, AIAA 15th Aerodynamic Testing Conference, San Diego, CA, paper no AIAA-88-1997, May 18-20, 1988.
6. Meyers, J. F.: *A Three Dimensional View of Velocity Using Lasers*, 10th International Invitational Symposium on Unification of Finite Element Methods in Theory and Test, Worcester, MA, July 18-19, 1991.
7. Meyers, J. F.; and Hepner, T. E.: *Measurement of Leading Edge Vortices from a Delta Wing Using a Three Component Laser Velocimeter*, AIAA 15th Aerodynamic Testing Conference, San Diego, CA, paper no AIAA-88-2024, May 18-20, 1988.



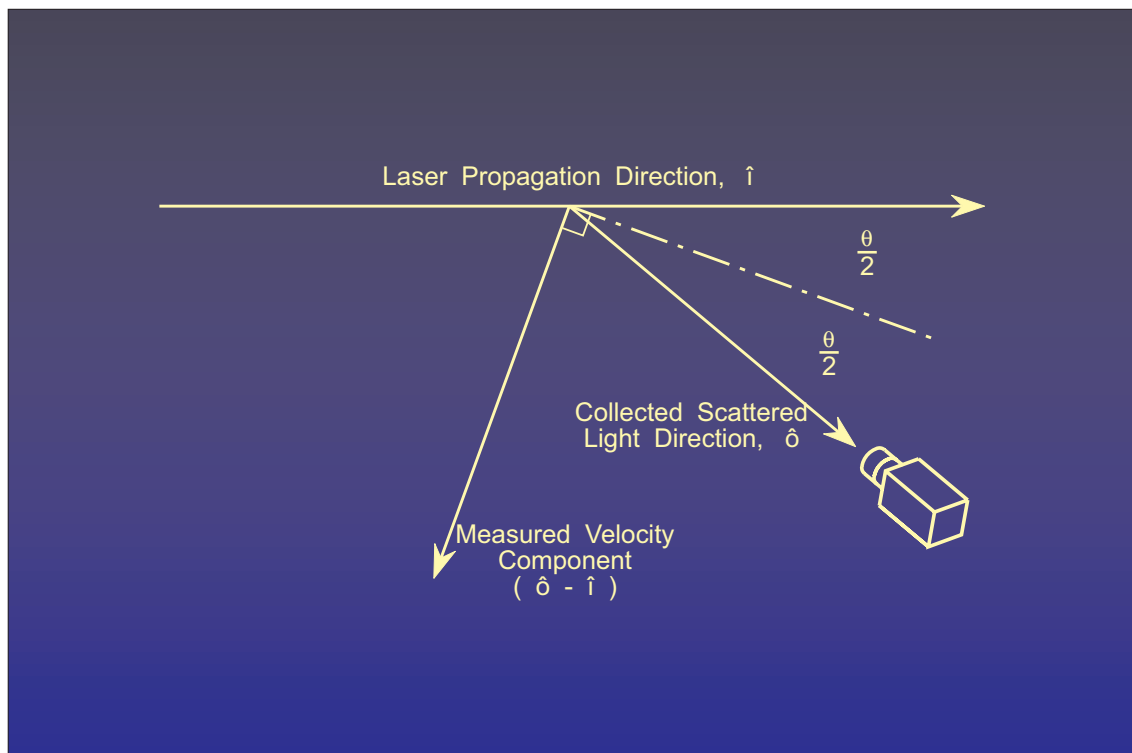


Figure 1.- Diagram depicting the velocity measurement direction based on the orientation of the laser propagation direction and the detector location.

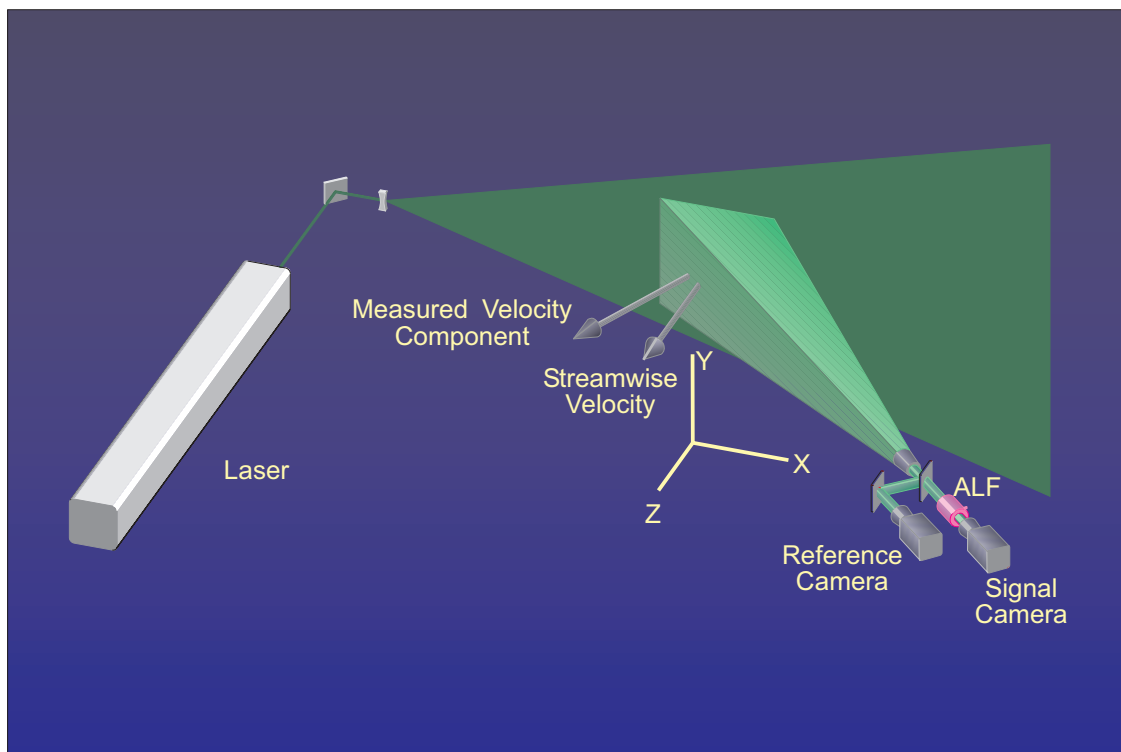


Figure 2.- Pictorial view of the Doppler global velocimeter used in the Basic Aerodynamics Research Tunnel.

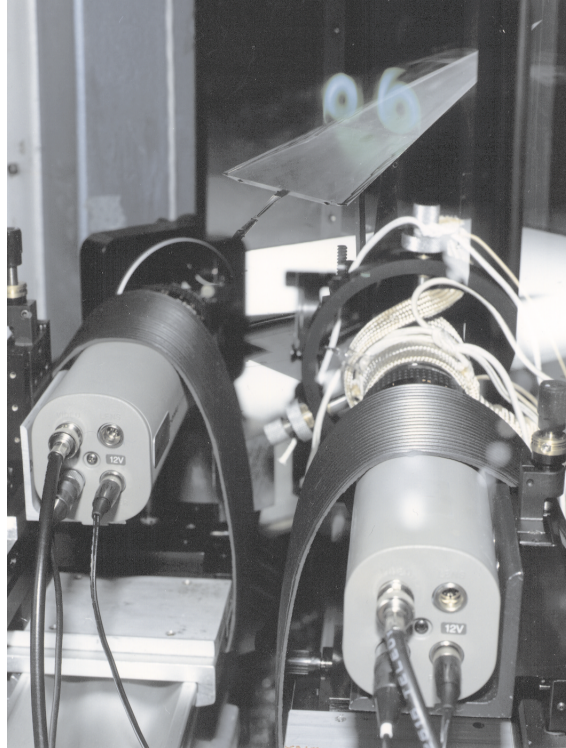


Figure 3.- Photograph of the Doppler global velocimeter installed in the Basic Aerodynamics Research Tunnel.

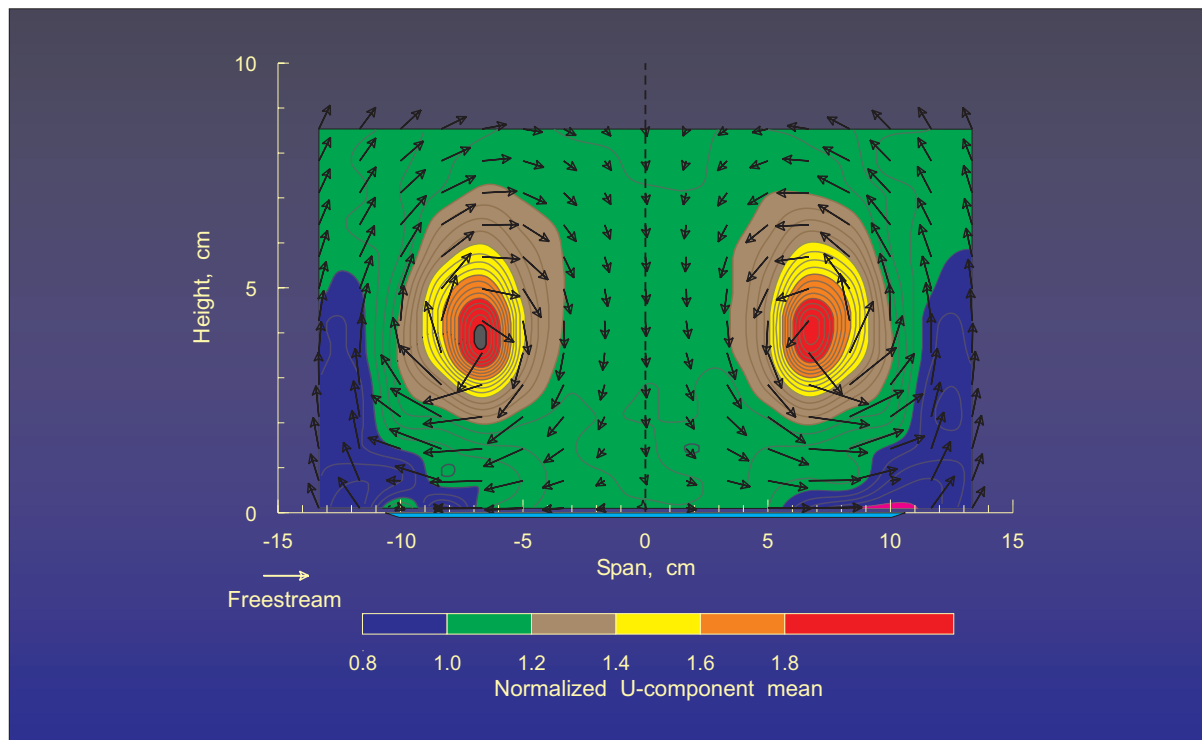


Figure 4.- Three component laser velocimeter measurements of the vortical flow field above a 75- degree delta wing at an angle-of-attack of 20.5 degrees.

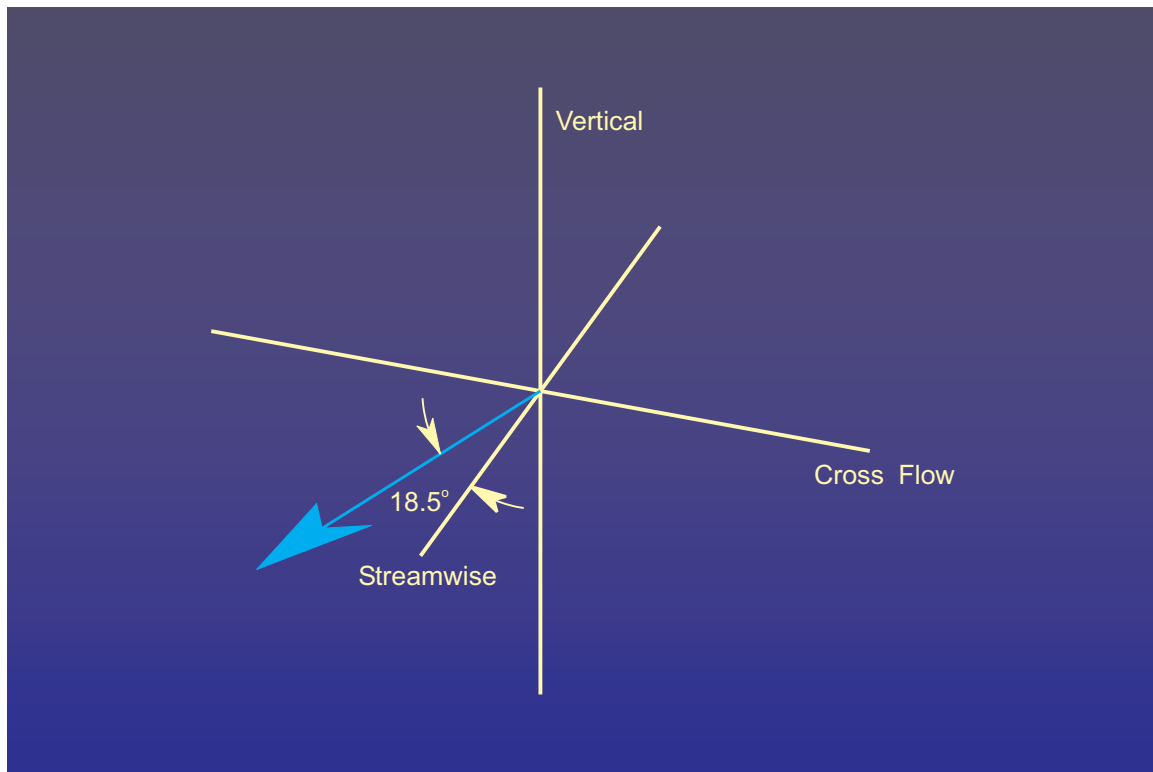


Figure 5.- Measurement direction for DGV operation in forward scatter mode.

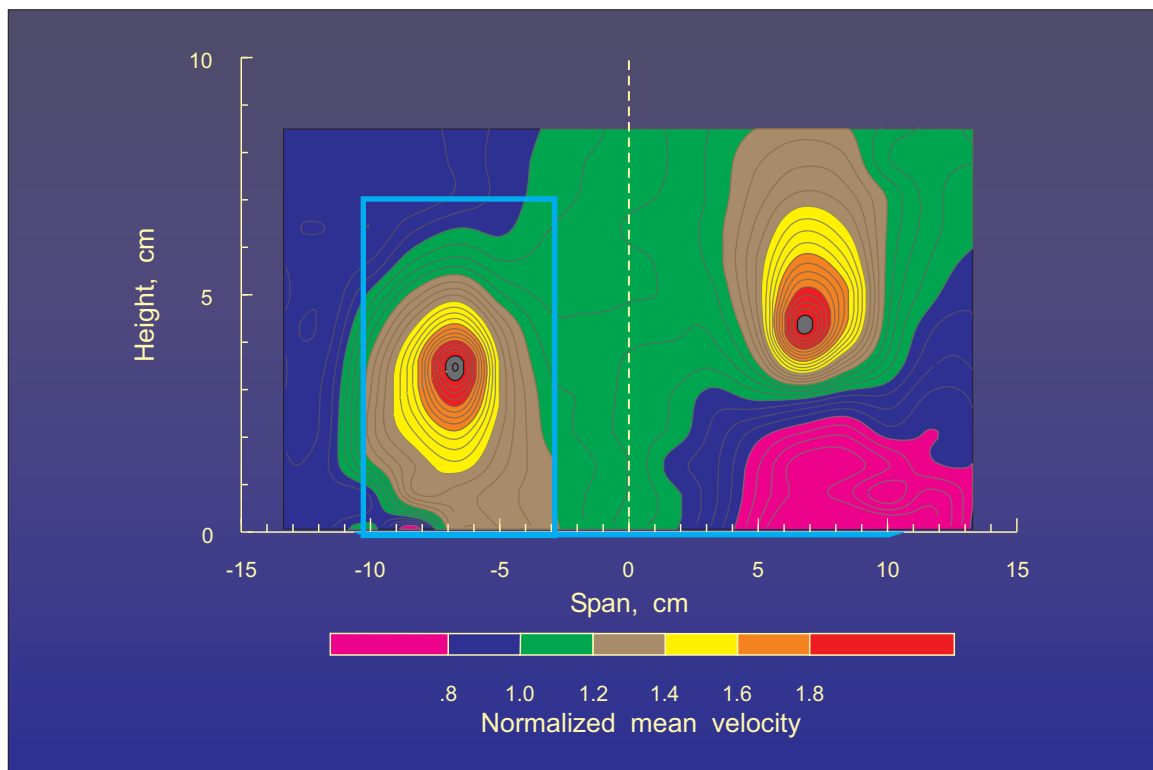


Figure 6.- Resolved laser velocimeter measurements along the direction 18.5 degrees from streamwise in the horizontal plane.

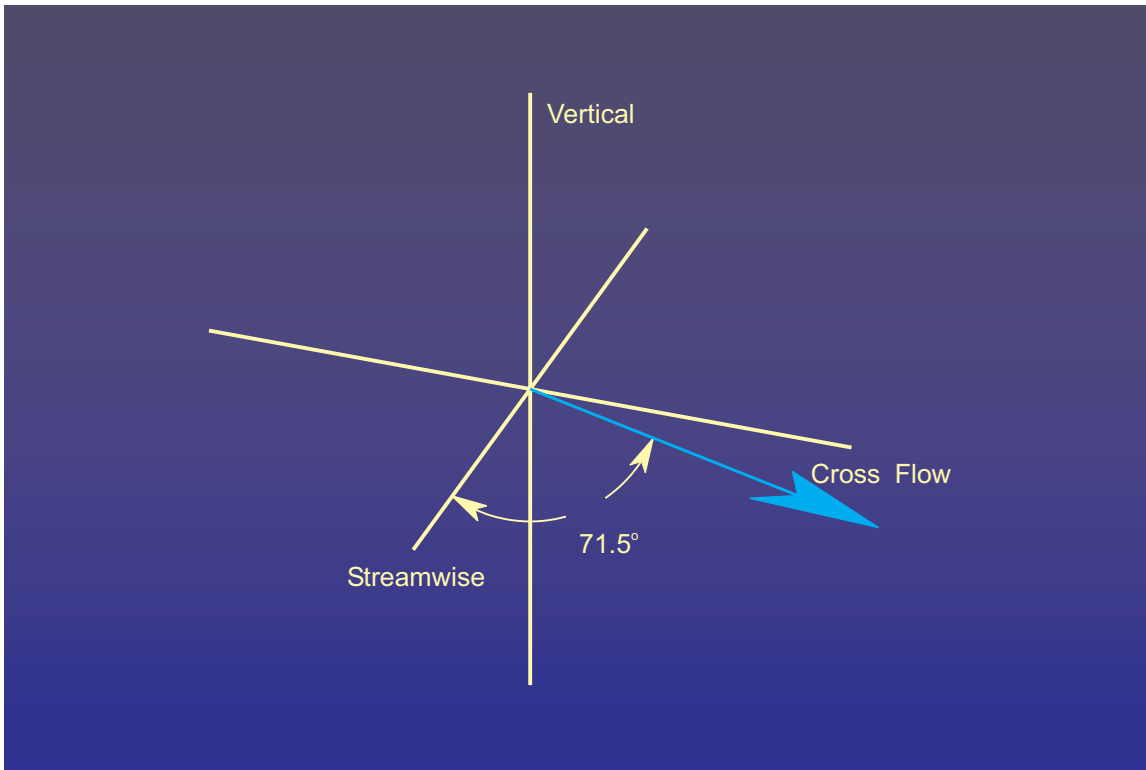


Figure 7.- Measurement direction for DGV operation in backscatter mode.

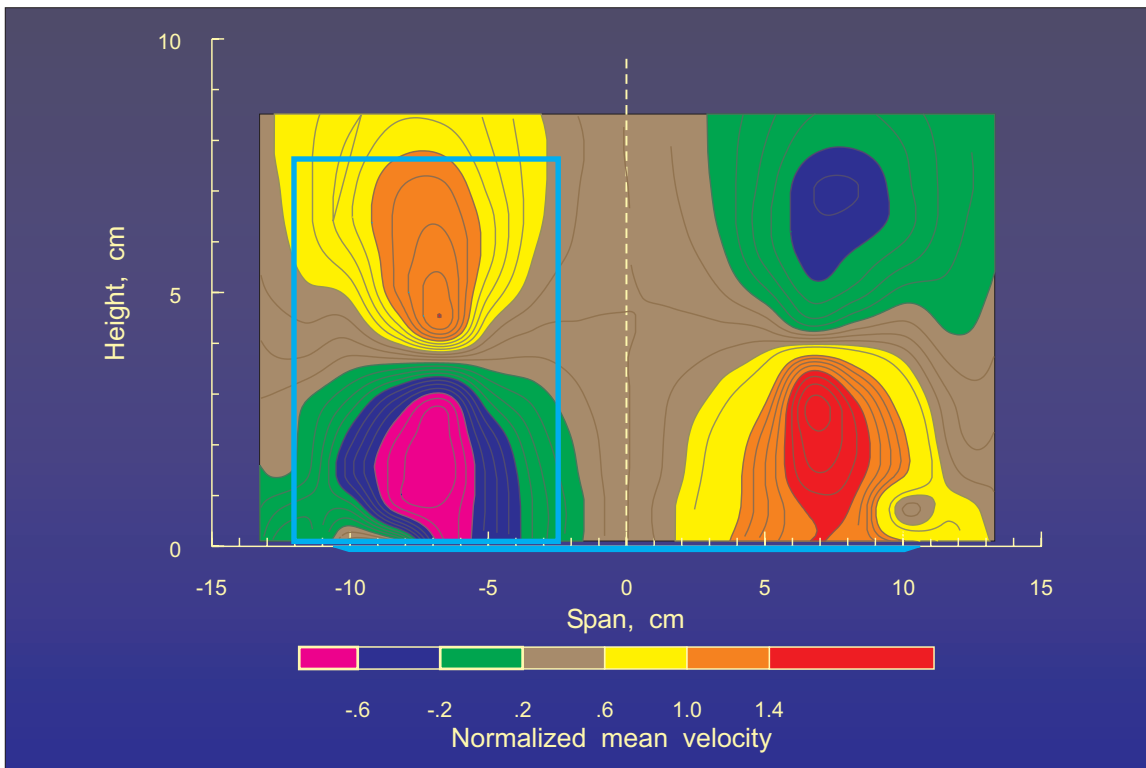


Figure 8.- Resolved laser velocimeter measurements along the direction  $71.5$  degrees from streamwise in the horizontal plane.

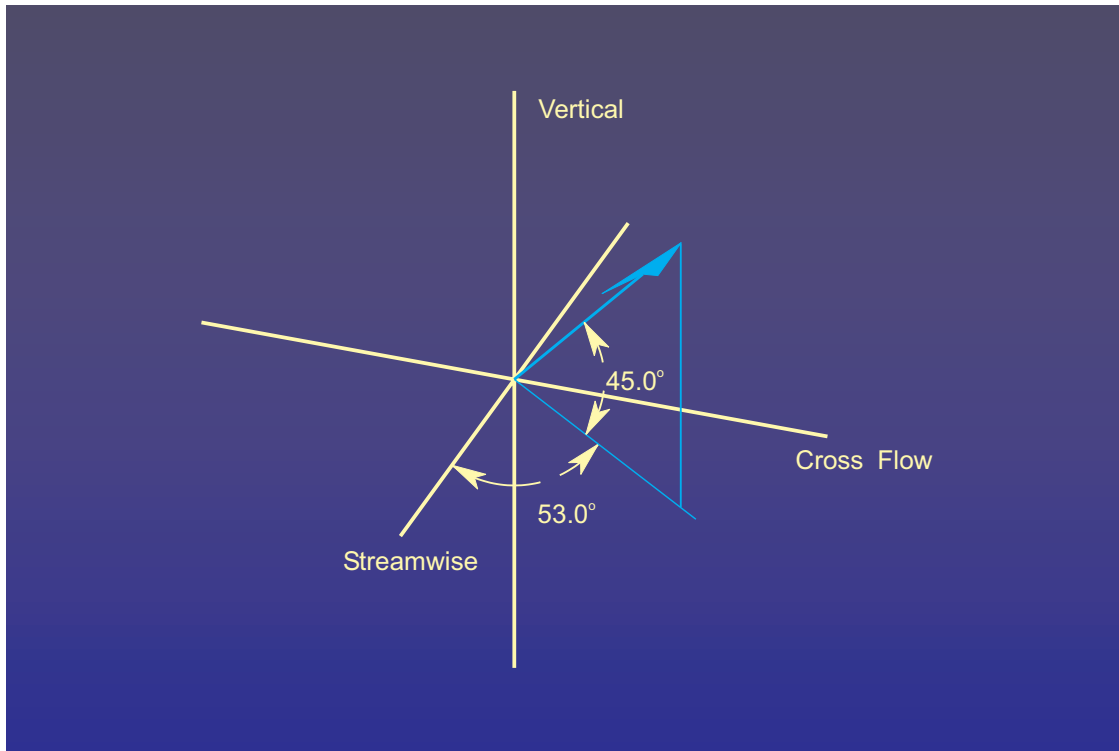


Figure 9.- Measurement direction for DGV operation in side scatter mode, (laser propagation from above).

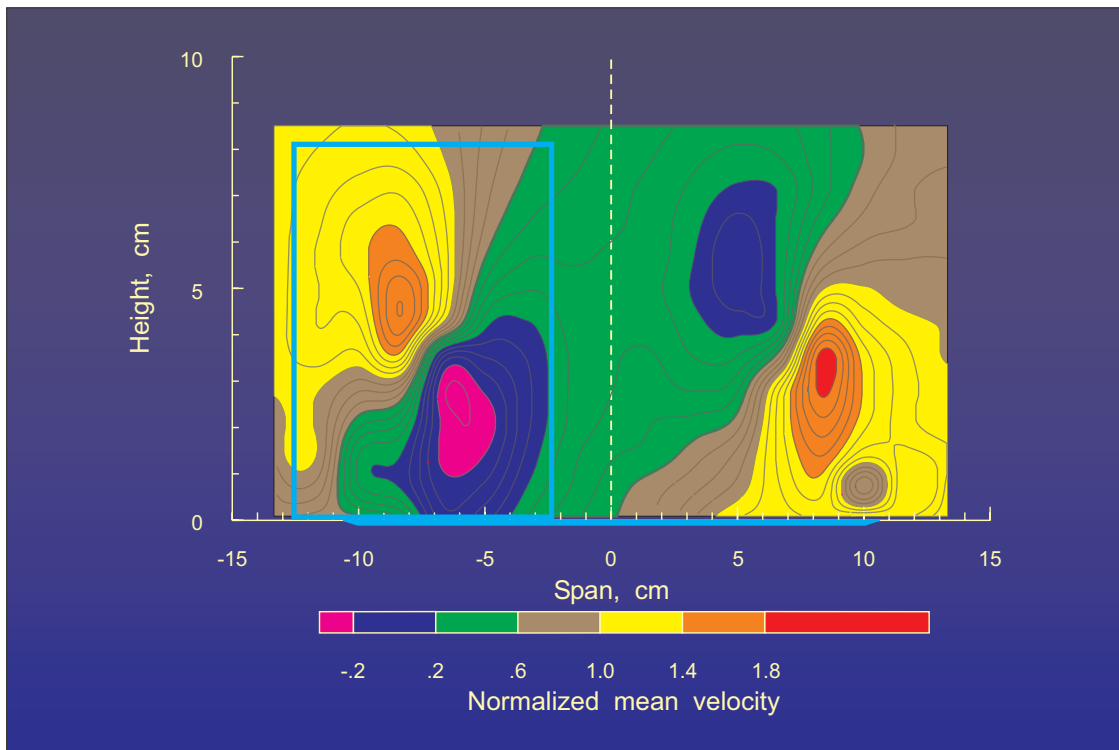


Figure 10.- Resolved laser velocimeter measurements along the direction 53.0 degrees from streamwise and 45.0 degrees above the horizontal plane.

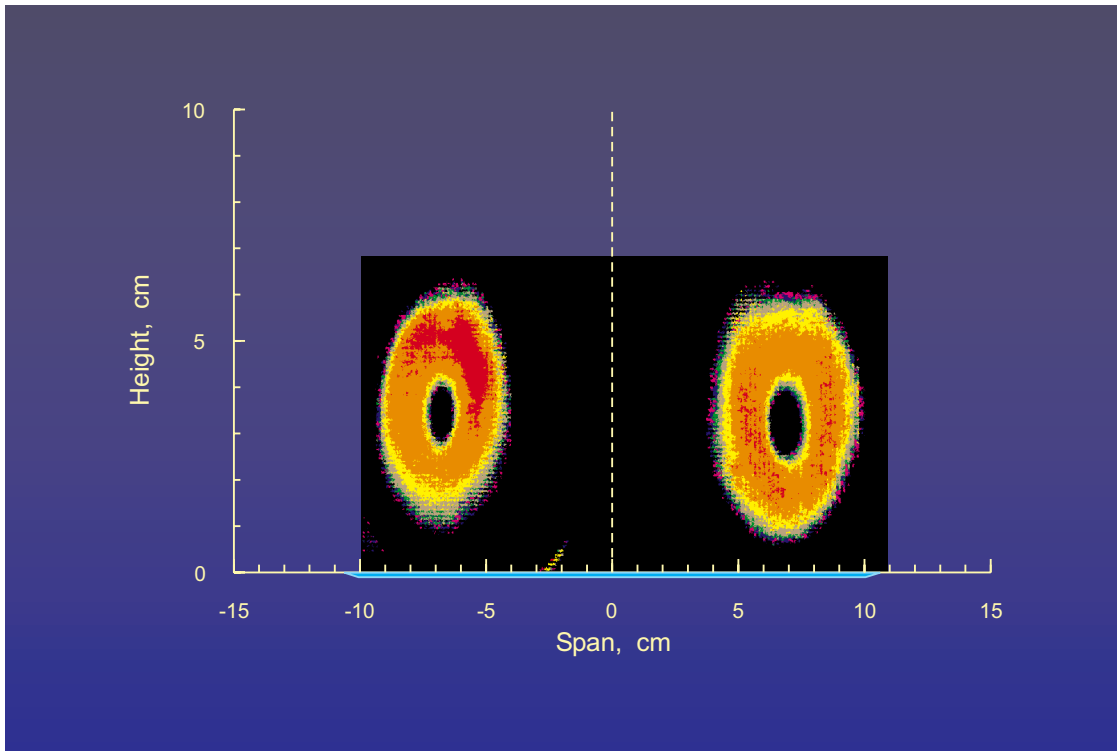


Figure 11.- Normalized light intensity (proportional to velocity) obtained by the DGV in forward scattered mode.

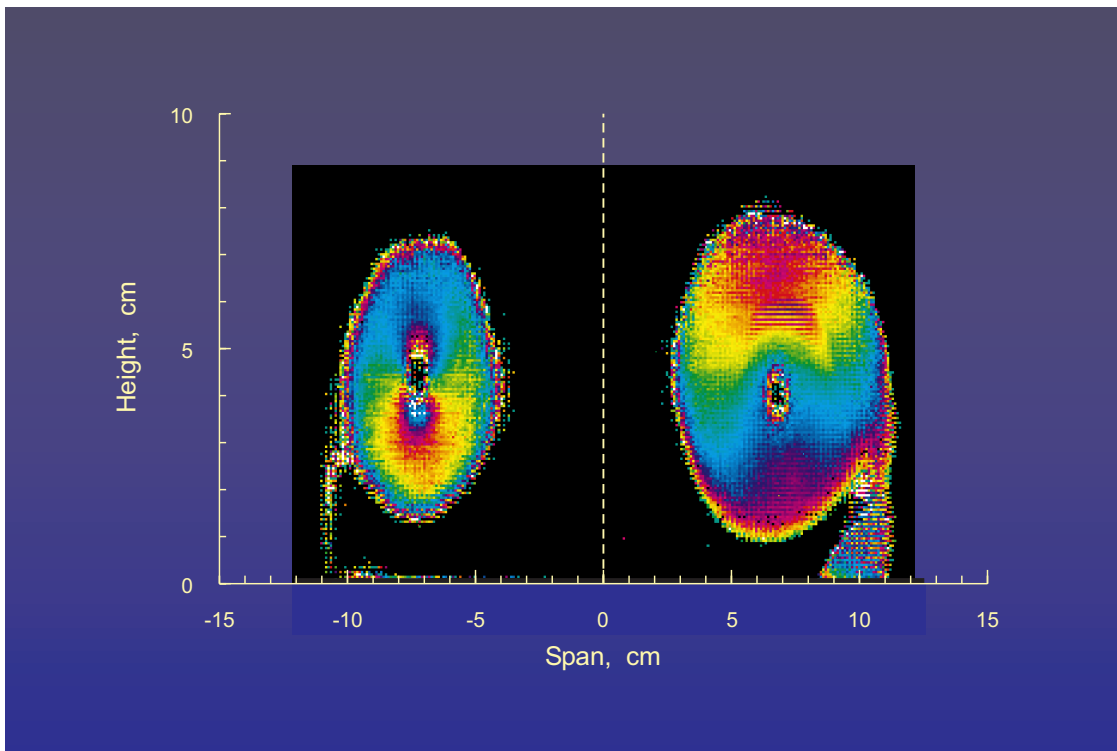


Figure 12.- Normalized light intensity (proportional to velocity) obtained by the DGV in backscattered mode.

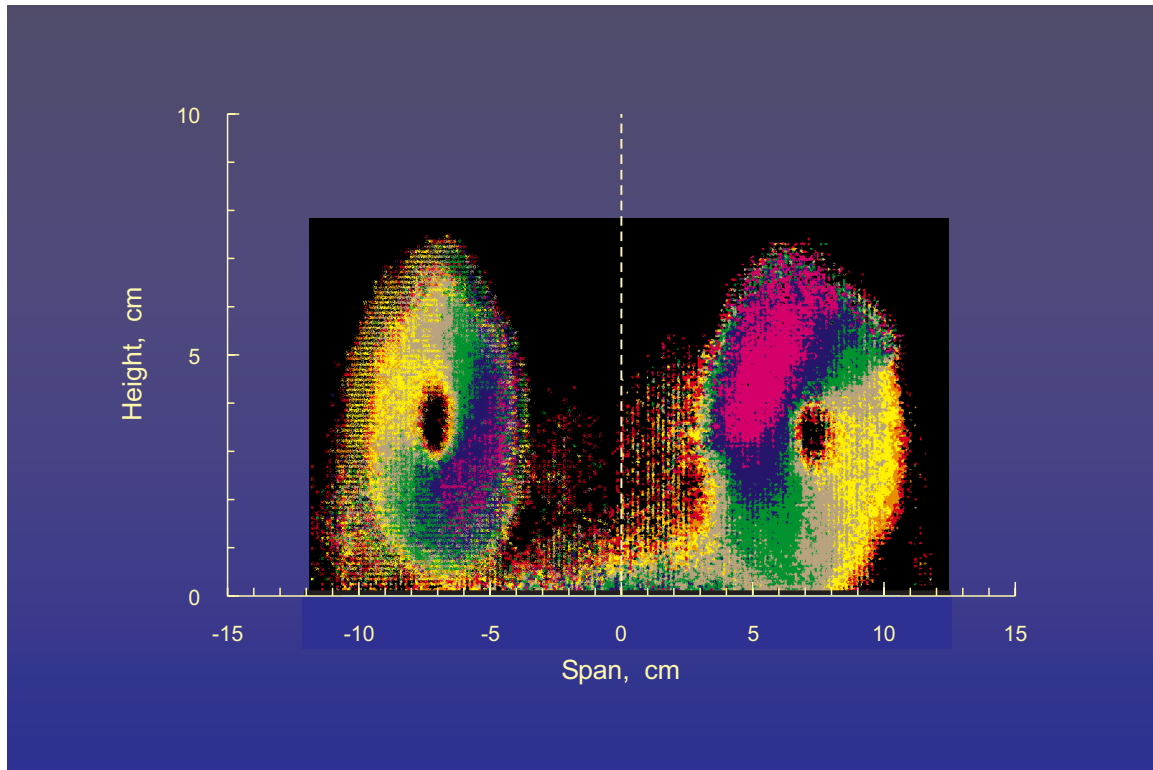


Figure 13.- Normalized light intensity (proportional to velocity) obtained by the DGV in side scattered mode, (laser propagation from above).

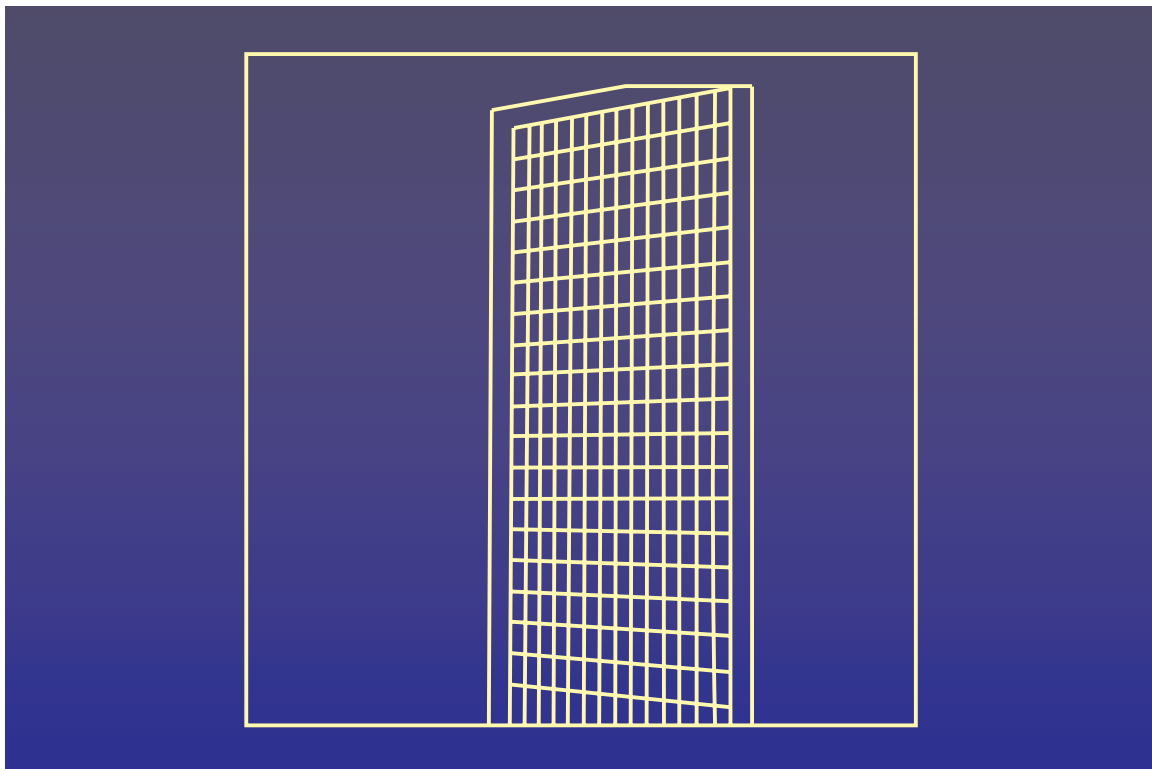


Figure 14.- Image of a square grid placed in the plane of the laser light sheet.

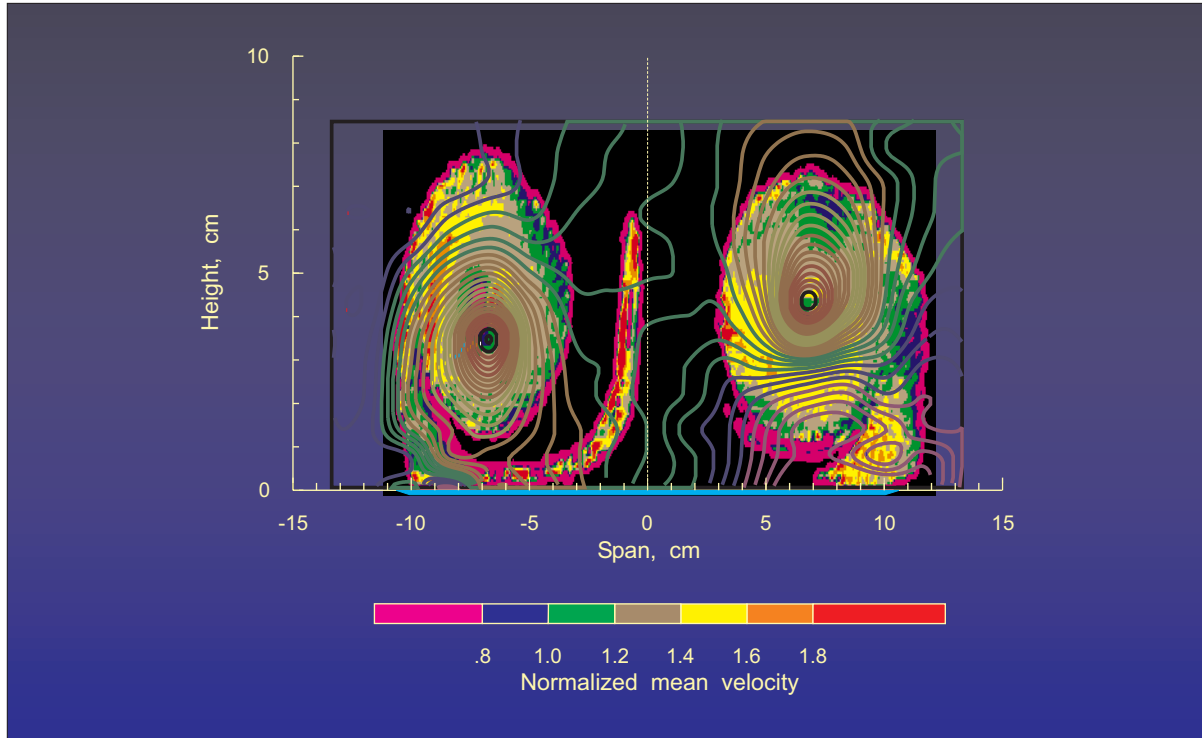


Figure 15.- Overlay of the DGV image obtained in forward scatter mode, figure 11, by the resolved LV velocity contours, figure 6.

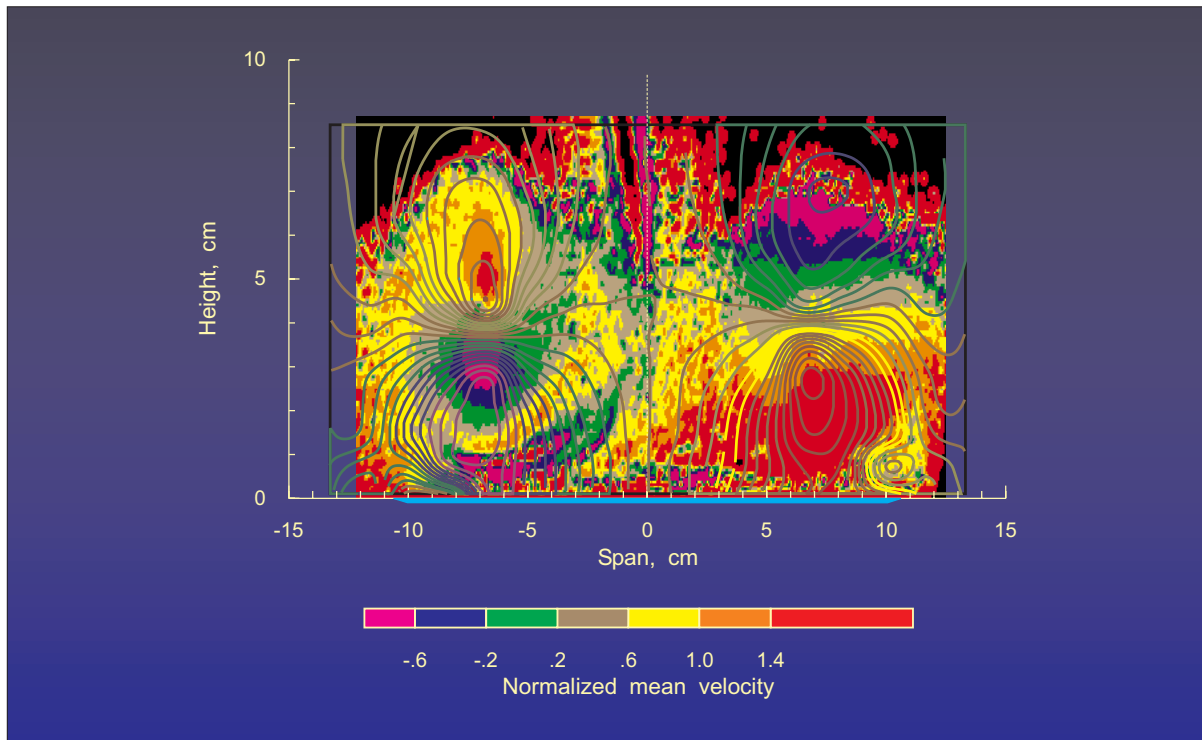


Figure 16.- Overlay of the DGV image obtained in backscatter mode, figure 12, by the resolved LV velocity contours, figure 8.



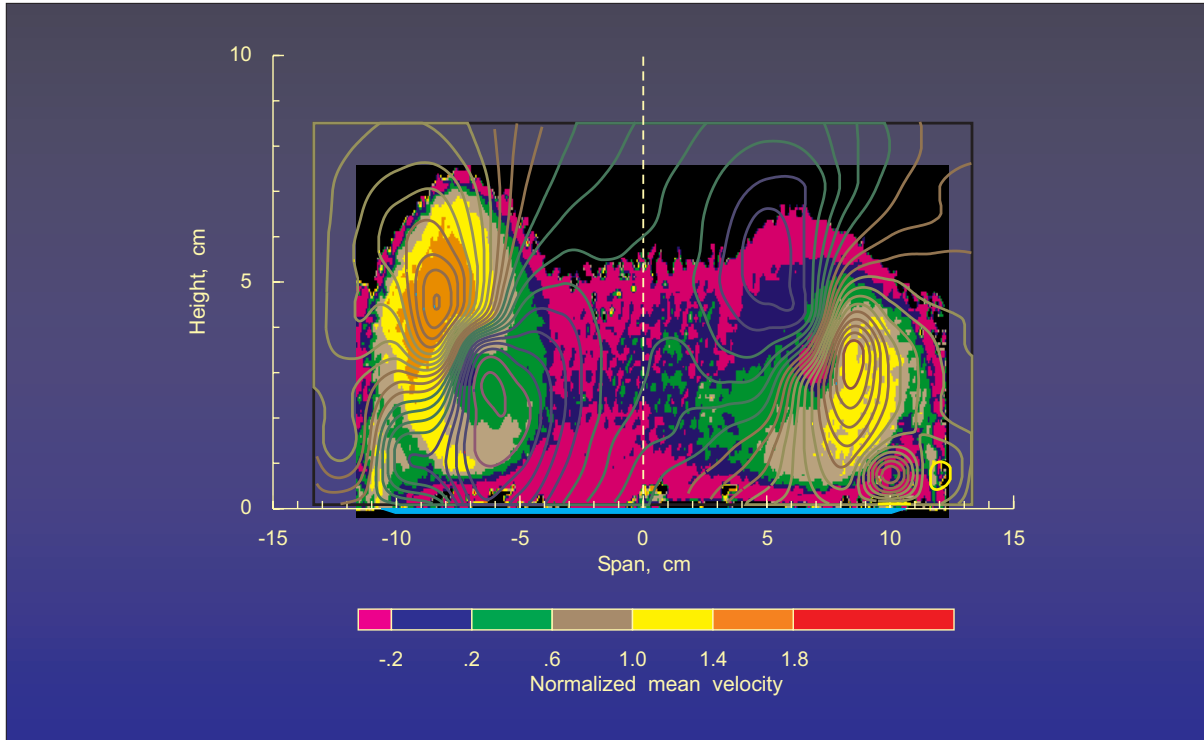


Figure 17.- Overlay of the DGV image obtained in side scatter mode, figure 13, by the resolved LV velocity contours, figure 10.